Explosive Risk and Structural Damage Assessment Code (ERASDAC)

Prepared by:
Michael W. Stahl
Mark G. Whitney
and
Joseph M. Serena, III, P.E.

Abstract

This paper describes the principles behind software developed for the purpose of evaluating siting of facilities where explosives are stored, processed, assembled or handled. The work was funded as a Phase I Small Business Innovative Research (SBIR) project that was solicited by the Department of Defense Explosives Safety Board (DDESB) and contracted through the U.S. Army Corps of Engineers, Huntsville Division (USAEHD) which also provided technical review and direction.

The objective of the software is to facilitate prediction of blast effects and associated hazards at acceptor buildings due to explosion accidents. The software is entitled Explosives Risk and Structural Damage Assessment Code (ERASDAC). The software operates on three levels. Level 1 provides a "quick" assessment of several generic types of building components by calculating component damage threshold distances that correlate to the user specified net explosive weight (NEW). Level 2 provides a site-specific and site-wide evaluation of all inhabited buildings for specified donors. At this level, inhabited buildings and donor facilities can be defined by choosing from an extensive library of pre-established buildings which are common to those found on-site or near DoD facilities. Level 3 allows detailed analysis of individual buildings. Here, the user can specify specific details of building structural members for analysis by the software.

The ERASDAC software is currently being expanded under a Phase II SBIR to include fragment and debris hazard prediction methods; improved free-field blast prediction methods which will address a variety of donor sources; improved building load prediction methods to address orientation, clearing time, drag effects, shielding, and backside loading; improved structural response algorithms; and relationship between building damage and risk of injury to building occupants.

1.0 Introduction

This paper reports on work completed under a Phase I Small Business Innovative Research (SBIR) project that was solicited by the Department of Defense Explosive Safety Board (DDESB) and contracted through the U.S. Army Corps of Engineers, Huntsville Division (USAEHD) which also provided technical review and direction. This work is being continued under a Phase II SBIR contract which was initiated during the preparation of this paper. Thus, while the Phase II direction is discussed herein, results will await future discussions.

The objective of this project is to develop a user friendly software package for use in the prediction of blast effects and associated hazards at acceptor buildings due to explosion accidents. The software is applicable to the Department of Defense (DoD) and contractor facilities where high explosives are

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1996**	2. REPORT TYPE	3. DATES COVERED **00-00-1996 to 00-00-1996**

4. TITLE AND SUBTITLE **Explosive Risk and Structural Damage Assessment Code (ERASDAC)**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Corps of Engineers,Army Engineering and Suuport Center, Huntsville,PO Box 1600,Huntsville,AL,35807-4301**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM000767. Proceedings of the Twenty-Seventh DoD Explosives Safety Seminar Held in Las Vegas, NV on 22-26 August 1996.

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

stored, processed, assembled, or handled. The name selected for this software is ERASDAC which stands for “Explosion Risk and Structural Damage Assessment Code.”

DoD facilities and those owned by DoD contractors at which high explosives are stored or handled must be situated to provide reasonable protection to personnel in the event of an explosion accident. Explosion hazards include airblast, donor fragmentation (primaries, donor building debris, other fragments), thermal hazards, and acceptor generated hazards (building collapse and falling components). Protection is provided by separation, protective construction, or a combination thereof. As distance increases between the explosion source and the acceptor building, the blast strength and fragment density decreases. Protective construction can also reduce injury or prevent propagation.

Defense of Department facilities must meet exposure limit criteria established in DoD 6055.99 (1991) as well as responsible service branch requirements. DoD contractors must meet similar criteria in DoD 4145.26M (1988). For example, limit criteria for inhabited buildings states that exposure must be less than 1.2 psi free-field over pressure, one per 600 sq ft hazardous fragment density, and 0.3 $cal/cm^2/sec$ thermal hazard. Compliance with these limits can be shown through detailed analysis where site specific exposure to blast overpressures and fragment density are quantified or through adoption of non-site specific "default" distances, called Quantity-Distance (Q-D) relationships. The "default" Q-D inhabited building distance for blast is K40 where:

Distance (ft) = 40(NEW)1/3
NEW = Net Explosive Weight

This criteria is considered to also cover thermal criteria. The "default" criteria for fragments (including primaries and donor building debris) is 670 or 1,250 ft for below and above 100 lb NEW respectively. These default relationships do not account for protective construction, differences in donor construction debris source, casing configurations or other site specific information.

Buildings sited according to established criteria place personnel at a level of exposure to explosion effects which has been deemed acceptable by the DDESB. The risk of injury, however, is not quantified. Such an assessment would require site specific consideration of the donor and acceptor building construction. Construction of the donor building affects the blast field and the building as a source of debris. Construction of the acceptor building affects whether the occupants are protected or if they are exposed to additional hazards from structural failure or collapse of the acceptor building or is components. In order to quantify the risk of injury to occupants of an acceptor building, the structural response of that building must be determined and failure identified.

The long term goal of this SBIR study (including future phases) is to develop ERASDAC into a versatile and user friendly computer program which can be used to determine the risk of injury at acceptor buildings from an explosion accident at any given site. Also, assessment of facility property damage can be made. Note that the goal of this software is to quantify explosion consequences and not to assess the likelihood that the accident would take place. A complete risk assessment would consider both parts of the situation; the probability that a given accidental explosion would occur and the risk involved in the consequences of that event. The goal of this study relates to the second part only.

Fortunately, much previous work had been completed which addresses the consequences of explosions. The "state-of-the-art" is such that blast effects, building response and associated hazards can be reasonably predicted. Currently, the methods to make such predictions reside in a variety of technical reports and in some software packages. Injury risk calculations could be made using this existing technology; however, even one case study would require time consuming hand calculations combined with the use of software that was developed for other purposes but can give pertinent answers. This includes prediction of blast loads, fragment hazards, and structural responses followed by comparisons with human tolerances. Such a study must be completed by a trained analyst. It is the objective of the project to develop a site risk assessment software tool to automate this process and allow quick assessments.

The long term goal for the ERASDAC software includes the following:

- Compare building siting with "default" Q-D relationships.
- Evaluate site specific construction of donor and acceptor buildings.
- Predict the blast field, debris throw, and fragmentation that could result from an accident at a particular donor building and explosive configuration taking into account the construction of that building and nearby barricading.
- Predict blast loads, fragments and debris at acceptor buildings, accounting for shielding and barricading.
- Predict blast loads on various building surfaces, accounting for building orientation, clearing time, drag effects, and backside loading.
- Predict structural response and failures of acceptor buildings.
- Predict window failures, residual velocities, and fragment sizes.
- Determine risk of injury to building occupants.
- Determine risk of injury to persons outside.

In Phase I, the scope was limited to airblast hazards at acceptor buildings and the risk of injury to their occupants. Also for Phase I, the Potential Explosion Site (PES) was treated as an unconfined surface burst. Debris hazards, primary fragment hazards, confinement at the source, window hazards, shielding and barricading, and risk of injury to persons in the open are left for future phases. Parts of the Phase I ERASDAC made use of existing public domain software. In particular, the FACEDAP (1993) program with its main computational subroutine BDAMA.EXE was selected for use in calculation of building damage. New programming was developed utilizing Visual Basic™ to provide a Windows™ compatible software package.

The Phase I ERASDAC software includes three levels of analysis. Level 1 provides an overview of hazards surrounding a single PES. Level 2 provides building damage and associated hazard assessment in a quick-look format addressing all donor and acceptor buildings on site. Level 3 provides a detailed assessment of damage to an individual acceptor building.

2.0 Level 1 Analysis

The Level 1 of ERASDAC is intended to provide an overview of explosion hazards surrounding a specific potential explosion site. The analysis provides general information regarding explosion hazards at various distances surrounding the location of a potential explosion. Various hazard levels are specified and determination of the "threshold" distance for each hazard is made.

2.2 Description of Level 1 Hazard Levels

Seventeen different hazard levels were chosen for the Level 1 analysis. These are listed below:

- Residential Window Breakage, 28 inch x 36 inch x 3/16 inch
- Commercial Window Breakage, 48 inch x 96 inch x 1/4 inch
- Unreinforced Masonry Walls Crack
- Unreinforced Masonry Walls Collapse
- Reinforced Masonry Walls Crack
- Reinforced Masonry Walls Collapse
- Wood Roof Joists Crack
- Wood Roof Joists Failure
- Wood Wall Studs Crack
- Wood Wall Studs Failure
- Residential Brick Walls Crack
- Residential Brick Walls Failure
- Metal Panel Walls Bend
- Metal Panel Walls Collapse
- Threshold for Eardrum Rupture, K24
- Temporary Threshold Shift, K328
- OSHA Hearing Protection Threshold, K800-K1000

These various levels of hazards are considered to be important to most situations. For each hazard level the software calculates a "threshold" distances which is the greatest distance at which this hazard will exist. In addition, the software calculates whether or not the threshold value has been exceeded at various distances, responding with a yes or no answer. The Level 1 screen includes a spreadsheet which summarizes the information.

2.3 Development of R-W Diagrams From P-i Diagrams

Determination of threshold distances of the various hazard levels indicated above are determined based on a procedure developed under the Phase I SBIR. This included the development of "Range-Weight" (R-W) diagrams. A R-W diagram utilizes the same information that is contained in a Pressure-impulse (P-i) diagram but is specific to a single explosion scenario, in this instance an unconfined hemispherical surface burst. For a hemispherical TNT ground burst at Standard, Temperature and Pressure (STP), at each standoff and charge weight combination, a unique pair of pressure and impulse is obtained. These pressure and impulse pairs are utilized to convert a P-i diagram for a specific structural member over to a R-W diagram. The surface burst curves in TM5-

1300 were used to develop the R-W diagrams along with the P-i diagrams developed under the FACEDAP (1993) program.

The approach taken to develop the R-W diagrams starts by obtaining curve fit equations to pressure and scaled impulse vs scaled distance ($Z = R/W^{1/3}$) for a hemispherical surface burst provided in TM5-1300 (1990). It was necessary to extend the range of the TM5-1300 curves, which stop at Z=100 $ft/lb^{1/3}$, out to Z=1,000 $ft/lb^{1/3}$ since several of the damage levels chosen are based on low pressures. Sach's scaled curves in Baker (1968) were used for this purpose.

The conversion from a scaled P-i diagram in FACEDAP to a R-W diagram followed these steps:

1. Select values of span, spacing, section properties, weights, strengths, and boundary conditions of a particular structural member.
2. “Unscale” the non-dimensional P-i diagram using the values in step one to create a dimensional P-i diagram..
3. Use the curve fits for the pressure and scaled impulse vs. Scaled distance (Z) data to calculate R-W combinations as follows:
    a. Select a p and i pair from the unscaled (dimensional) P-i diagram.
    b. Use the p value and the pressure vs Z curve fit to chose a Z value.
    c. Place this Z in the scaled impulse vs. Z curve to pick a corresponding value of scaled impulse, $I/W^{1/3}$.
    d. Use this scaled impulse and the i value from the P-i diagram to calculate W.
    e. Use W to unscale the scaled distance, $Z = R/W^{1/3}$.
    This process provides a value of R and W which will produce a pressure and impulse which falls on the P-i diagram. Iteration of this process over the range of the P-i diagram develops a collection of points from which a R-W plot is developed
4. Finally, Tablecurve ™ is used to develop a curve fits to the R-W plots over the range of interest. These curve fits are programmed into SafeSite.

Several of the Level 1 hazards do not have an existing P-i diagram and these had to be developed as described in the sections below.

2.3 Window Breakage

Two window sizes were included for the Level 1 list of hazards. A small window, representative of that found on residential buildings, was selected as 28 inch x 36 inch x 3/16 inch annealed glass. A large window, representative of a commercial building, was selected as 48 inch x 96 inch x 1/4 inch annealed glass. Two approaches were taken to address window breakage; one for the calculation of threshold distance and one for the calculation of percent window breakage at the various distances specified on the Level 1 spreadsheet.

The calculation of threshold distances utilize R-W plots that were developed for the two window sizes. The procedure used to create these plots included using the program SAFEVUE (1993) to obtain single-degree-of-freedom (SDOF) equivalent parameters.

The next step was to establish asymptote valves for the impulsive and pressure realms. These were calculated based on classic energy equations for elastic systems.

$$\text{Impulsive asymptote: } I_a = (m_{eff}\ r_u\ x_m)^{1/2}$$
$$\text{pressure asymptote: } P_a = 1/2\ r_u$$

The maximum deflection, x_m, is set as the elastic limit, x_e , which is compatible with SAFEVIEW assumptions. The effective mass, m_{eff}, is the real mass times the load mass factor,

These values were input into the general FACEDAP P-i curve formula (eq. 1) to relate combinations of pressure and impulse in the dynamic realm (between asymptotes).

The standard P-i curve fit formula used in FACEDAP is:

$$P = \frac{O.4\ (P/2 + I/2)^B}{I + I_a} + P_a \qquad \text{(eq. 1)}$$

Where I_a = Impulse asymptote value.
P_a = Pressure asymptote value.
P = Arbitrary pressure value on curve.
I = Impulse value corresponding to P on curve.
B = Shape factor.

Once this was accomplished, P-i plots and R-W plots were made for each window. These allow determination of a threshold of breakage distance since they are break/no break type curves. While such a number is useful, it does not represent the nature of glass failures. Based on observations made in past explosion accident investigations, it is clear that window breakage tends to be statistical in nature. All natural phenomena seem to vary due to irregularities in physical properties; however, this attribute is exaggerated for glass failures. Window breakage does not start/stop at a given distance. There tends to be a gradual decrease in window breakage with distance. This is due to age of the glass, its condition, its orientation to the blast, focusing effects, and many other factors. To address this in Level 1, an existing window breakage probability relationship developed by Reed et.al., (1963) was chosen as a model. The work was utilized here to calculate the percent of windows which can be expected to break at various distances.

2.4 Wall and Roof Damage for Various Building Constructions

Damage predictions for a variety of building constructions were included in the Level 1 of ERASDAC. Addressed are masonry, wood, brick, and metal panel buildings. For each, two damage levels were addressed, minor damage and failure, each for wall and roof members. The approach taken for all of these building types was the same, as follows:

- "Typical" member sizes, spans, and spacings were selected to represent building components which were considered common for conventional construction.

- The "typical" member values were used to "unscale" the non-dimensional FACEDAP P-i diagrams.
- Components for which FACEDAP P-i curves were not available required development of new P-i curves. These were developed either using first principles or modifying existing FACEDAP curves. An example of the latter is a wood stud wall with a brick exterior. The wood stud and the masonry do not act as a composite section and were treated as two springs in parallel. Pressure and impulse asymptotes from the FACEDAP masonry and timber P-i curves were used to define the P-i diagram for a stud wall with brick. The pressure asymptotes were added while the impulse asymptote was defined using the strength from the wood stud and mass from the brick. "Typical" member values were used to develop these dimensional P-i diagrams.
- The dimensional P-i curves were converted to R-W diagrams as describe earlier, thus relating charge weight and distance to a particular damage level for each type of building component.

2.5 Noise and Ear Damage

Three noise hazard levels were selected for the Level 1 analysis. These include the following:

- Threshold of eardrum rupture = 185 db
- Temporary threshold shift (TTS) = 160 db
- OSHA hearing protection threshold = 140 db

The threshold of eardrum rupture and TTS are reported in TM5-1300 but date back to earlier research. See Baker et,al., (1983) for a historical perspectus. These are well established to occur at 185 db (5 psi) for eardrum rupture and 160 db (0.217 psi) for TTS. The 5 psi reflected value corresponds to K24 which is a default Q-D value. TTS appears to be the basis of the K328 exposure limit specified in the MIL-STD-389 for intentional detonations, as this is approximately the reflected pressure at that distance. The OSHA impulse noise limit of 140 db corresponds to a free-field overpressure of 0.03 psi, which will not cause TTS but is high enough to cause significant annoyance and/or concern (fear) by those exposed. History has shown that sound pressure levels in this range have also resulted in some minor damage claims, based on experiences near test ranges as documented in DOE/TIC-11268 (1992).

These pressure levels were included in the Level 1 analysis. Since they are related to pressure alone, all can be expressed as K factors, for a surface burst, as summarized below.

- Threshold of eardrum rupture = 5 psi reflected = K24
- Temporary Threshold (TTS) = 0.15 psi reflected = K328
- OSHA Noise annoyance/concern = 0.03 psi free-field = K800 - K1000

The noise level of 140 db (0.03 psi) falls in a range of K800 - K1000 based on inherent far-range scatter as described in DOE/TIC-11268 for low overpressures. The mean value is K800 but for Level 1 analysis we will report based on the upper limit, K1000.

3.0 Level 2 Analysis

Level 2 of ERASDAC is intended to provide a site-wide evaluation which includes addressing various donors and various acceptor buildings located at a particular installation. Donors are characterized by their NEW and considered as an unconfined surface burst. Acceptor buildings are chosen from a library of buildings which are considered as common construction found at many facilities. In this level, a quick assessment of building damage and the percentage of failed components at each acceptor building is calculated. Plots of information are provided from two different points of view, a donor based analysis and an acceptor based analysis.

All calculations in the Level 2 analysis are made by converting the global donor and acceptor positions to relative distances, then making a call to the BDAMA.EXE routine to perform damage calculations. Structural information concering all acceptor buidings are selected from a library of building data files which are compatible with BDAMA.EXE.

Information returned from BDAMA.EXE includes the percent of building damage and the percentage of failed components. For a detailed description of these two quantities refer to the FACEDAP Theory Manual (1993). The percent of building damage is calculated by averaging the percent damage to all individual components, which are determined from component P-i diagrams. A "weighting" system is used to allow placing more significance on important structural components. The percent of building damage offers a description of what happens to the building but does not directly address risk of injury to occupants. Because injury occurs from the collapse of building components, we have included reporting the percentage of failed components. The percentage of failed components provides a qualitative measure of risk of injury to building occupants.

Level 2 analysis also reports free-field pressure, impulse, and effective duration at each acceptor. These calculations are made using the pressure and scaled impulse vs. scaled range for hemispherical surface bursts taken from TM5-1300. The effective duration is calculated for a triangular shock pulse shape which will be shorter than that obtained from Figure 2-15 of TM5-1300, which is for an exponential decay pulse shape. These values are based on distance measured from the donor coordinate to the center of the acceptor building.

3.1 Acceptor Buildings Library

Currently there are 24 acceptor buildings established in the library of typical buildings. These include masonry construction, timber construction, reinforced concrete buildings, and metal panel buildings. The first 13 buildings are those which were utilized in FACEDAP (1993). Of these 13, the first 12 were originally developed for the Blast Vulnerability Guide (1987) with the thirteenth added during the FACEDAP effort. Under this project, 11 new buildings were developed.

3.2 Donor and Acceptor Input

Information regarding the location of donor buildings or acceptor buildings are specified in the software using a global X-Y coordinate system. The selected coordinate system can be arbitrary as long as the same global system is utilized for all donors and acceptors. For example, choose positive

Y as due north, positive X as due east and 0,0 at a convenient location for calculating X,Y dimensions. Relative distances between donor and acceptors are calculated by the software based on the input X-Y coordinates.

Each donor is specified by defining X-Y coordinates in the global coordinate system as well as the NEW. Acceptor information includes X-Y coordinates in the global coordinate system, selection of the building type from the building library, and identification of the orientation angle between the building and the global coordinates. The orientation angle is measured relative to the X axis, rotating in a counter-clockwise direction to an outward normal vector from the front of the building.

3.3 Donor Analysis

In ERASDAC Level 2, the user can chose to preform a donor based analysis. Once the donor is selected and the analysis is executed, the software iterates on all acceptor buildings to determine percent building damage and the percent of failed components for each building. This information is displayed in a spreadsheet along with free-field pressure, impulse, and effective duration predicted at each of the acceptor buildings for an explosion at the selected donor.

The user can then select to plot blast contours for that specific donor. The blast contour plot is generated and positioned such that the donor is at the origin of the plot. Circular blast contours are drawn about the donor location and the various acceptor buildings are drawn on the plot. Pre-selected contours are plotted based on U.S. and NATO Q-D default values.

3.4 Acceptor Analysis

The acceptor analysis begins by selecting the subject acceptor building from the list of input acceptor buildings. The software then predicts free-field blast pressures and impulses from all donors at the selected acceptor building location along with percent building damage and percent of failed components for that acceptor caused by each of the defined donors.

An “acceptor-plot” is generated by the software. The plot is a P-i diagram type format. The plot includes selected wall and roof components along with a representative window for the building. The various donors are plotted as single points on the graph, based on free-field pressures and impulses. To account for the free-field values, the reflected oriented wall P-i diagrams were shifted to report an appropriate damage level. The relative locations of the plotted donor points to curves in the graph indicate the levels of damage that can be expected at the acceptor for each donor situation.

4.0 Level 3 Analysis

Level 3 of ERASDAC utilizes the FACEDAP program in its entirety without changes. Anyone desiring to utilize this level should refer to the FACEDAP Users Manual (1993) and the Theory Manual (1993) for all details and instructions. This provides for a very detailed analysis of a building, providing damage level calculations of all components. Buildings other than those in the library can be analyzed in Level 3, while Level 2 only considers those in the library.

5.0 Closure

A user friendly software package called ERASDAC was developed under the Phase I SBIR program which predicts blast effects and associated hazards at acceptor buildings due to explosion accidents. The three-level approach offers a choice of assessments capabilities. The Phase II SBIR is anticipated to address the above mentioned issues as well as many others to make significant improvements to this Phase I product.

6.0 References

"Ammunition and Explosives Safety Standards," DoD 6055.9-STD, 1991

Department of Defense Explosives Safety Board, "DoD Contractors Safety Manual for Ammunition and Explosives," DoD 4145.26M, July 1985, Change No. 2, April 1988.

"Facility and Component Explosion Damage Assessment Program (FACEDAP) Theory Manual," Southwest Research Institute, Project No. 06-5145-001, prepared for Department of the Army, Corps of Engineers, Omaha District, CEMRO-ED-ST, Contract No. DACA-45-91-D-0019, April 1993.

Baker, Wilfred E., P.S. Westine, J.J. Kulesz, J.S. Wilbeck, and P.A. Cox, "A Manual for the Prediction of Blast and Fragment Loadings on Structures," DOE/TIC-11268, U.S. Department of Energy, Amarillo, Texas, November 1980.

"Facility and Component Explosion Damage Assessment Program (FACEDAP) Users Manual," Southwest Research Institute, Project No. 06-5145-001, prepared for Department of the Army, Corps of Engineers, Omaha District, CEMRO-ED-ST, Contract No. DACA-45-91-D-0019, April 1993.